Advanced Hyperbaric Oxygen Therapies in Automated Multiplace Chambers

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Abstract—Hyperbaric (HBO) Oxygen Therapy is a method used to administer pure oxygen at a pressure which is greater than atmospheric pressure to a patient in order to increase the concentration of O2 in the tissues, blood and cells, and correct or improve certain conditions. The incorporation of automation and computer-based technologies thus makes the following possible: an almost perfect profile tracking, painless treatments (number of barotraumas is drastically reduced), repeatability, research, and the treatment of special conditions patients, such as pediatrics and patients with neurological diseases. The automated chamber presented in this work has been successfully tested over a 9 month period, with the application of approximately 540 standard treatments and 180 treatments for people with special conditions.

I. INTRODUCTION

A. Hyperbaric Medicine

Hyperbaric medicine [7], also known as hyperbaric oxygen (HBO) therapy, is a method used to administer pure oxygen at a pressure which is greater than atmospheric pressure to a patient in order to improve or correct certain conditions. Patients who receive HBO breathe pure oxygen in pressurized chambers, thus increasing the O2 concentration in their body’s tissues.

The use of HBO is becoming increasingly common in general medical practice as more doctors become acquainted with its applications, and it can now be used in the treatment of many diseases and conditions. The following indications are the approved uses of hyperbaric oxygen therapy as defined by the Hyperbaric Oxygen Therapy Committee of the UHMS (Undersea and Hyperbaric Medical Society): Air or gas embolism; Carbon monoxide poisoning; Cyanide poisoning; Clostridial myositis and myonecrosis (gas gangrene); Crush injury, compartment syndrome and other acute traumatic ischamias; Decompression sickness; Arterial insufficiencies (central retinal artery occlusion and enhancement of healing in selected problem wounds); Severe Anemia; Intracranial abscess; The necrotizing of soft tissue infections; Osteomyelitis (refractory); Delayed radiation injuries (soft tissue and bony necrosis); Compromised grafts and flaps; Acute thermal burn injuries.

Most of the treatments consist of the following steps: compression, treatment, and decompression. Compression is the most critical step, owing to the change in middle ear volume. Gas in these structures behaves in accordance with Boyle’s law, which describes an inversely proportional relation between pressure and volume. An inability to compensate for pressure changes results in tissue damage which, according to [9], is collectively referred to as barotrauma.

Slight barotrauma is common in children because their Eustachian tubes are narrow and become blocked easily, thus leading to severe pain and ear damage. One of the main problems is that of patients with a tracheostomy ball or tube. If pressure is not constant and oscillates at the bottom of the treatment (owing to chamber ventilation), the ball increases and decreases its volume periodically, provoking severe suffering in the patient and making it difficult to breathe. Critically ill patients who need automatic support ventilation, hemodynamic monitoring or parenteral drug administration, require a perfect pressure stabilization without oscillations. Patients that have been treated with radiotherapy in the nasopharynx area usually have more difficulties in compensating for pressure-volume changes. These difficulties result from the direct effect of ionizing radiations on healthy tissue surrounding the tumors, thus impeding the functioning of the patients compensation mechanisms. A controlled and automated system makes slower and more progressive ear volume changes possible, therefore allowing patients to compensate more easily.

The Medibarox Hyperbaric Center’s multiplace chamber (capacity for 25 seated people, ten gurneys or four ICU beds) has three compartments: a main chamber, an ICU (Intensive Care Unit), and a pre-chamber between them which allows them to be accessed from outside (see Fig. 1). It is very usual to have different treatments running inside the different chambers, and patients are frequently taken in and out of these chambers via the pre-chamber. The task of properly managing these situations manually is truly difficult.

Dealing with these problems on a daily basis does not currently make sense, when it is possible to incorporate known and tested industrial technologies in order to control the HBO treatments more safely and accurately, and with more complex and advanced profiles.

B. Control and Automation Requirements

Multicompartment and multiplace hyperbaric chambers require an automated control system able to track the treatments pressure profiles smoothly and without oscillations that can cause slight pains or even injuries to patients.
Furthermore, the automation architecture and the control program must be prepared to hold simultaneous treatments.

Medibarox Hyperbaric Center’s chamber has a pre-chamber between the ICU unit and the main chamber. The aim of the pre-chamber is to make possible the movement of patients and medical staff between compartments at different pressures, and to be able to introduce a doctor inside the chamber to treat a patient or to take out a patient in case of emergency. The pre-chamber can be seen as an elevator between different pressures (floors). This procedure is called pre-chamber protocol. These tasks must be carried out efficiently because usually are critical.

Other common procedure during treatments are alleviations. An alleviation is necessary when a patient has problems to compensate pressure changes and it consists on decreasing the pressure inside the chamber a defined value (usually 0.05 bar) and following a defined ratio (usually 0.1 bar/minute). Several consecutive alleviations can be necessary and when they are finished, the pressure profiles can continue. There are other procedures such as pauses (keeping constant the pressure), going back to surface (cancelling treatment and going back to ambient pressure following a profile), on-line pressure profile edition (changing the profile air volume change factor or treatment times during a treatment without altering it), etc. The aforementioned procedures must be decided to be executed in a chamber’s treatment without affecting the other simultaneous treatments.

It is necessary to have information of every physical variable that takes part in the process (pressures, pressure ratios, valve signals and positions,...), safety (oxygen concentrations, anti-fire system’s levels and pressures, batteries voltages, ...) or that affect patients’ comfort (temperature, humidity, noise, state of cooling and heating circuits ...). All this information has to be processed by the controller (for example a programmable logic controller (PLC)) and displayed in monitors.

II. CONTROL AND AUTOMATION OF A MULTIPLACE HYPERBARIC CHAMBER

Figure 2 shows the electromechanical scheme of the hyperbaric chamber installation configuration set-up. There are three different circuits with which to pressurize each chamber compartment (ICU, pre-chamber, and main chamber), each of which has a control valve and two safety valves. The air enters the chamber through pneumatic silencers. The decompression circuit is equivalent to the pressurization circuit. The PLCs read the sensors analog signals and control the analog and digital actuators. The PLC communicates with Industrial Ethernet via the computer and the HMI (Human Machine Interface) panel.

The treatments of hyperbaric oxygen therapy (Fig. 3) consist of three steps: pressurization or compression, bottom treatment, and depressurization or decompression. During a multiplace and multicompartiment HBO treatment, different incidents can occur and it is necessary to carry out some specific procedures that have been automatized in this work together with the pressure profile tracking.

1) Automation of Treatments and Medical Procedures: Different regulators have been designed depending on the volume of chamber to control, i.e. how many compartments are joined during a treatment. Therefore, each possible combination (ICU, pre-chamber, main chamber, ICU + pre-chamber, main chamber + pre-chamber, and ICU + pre-chamber + main chamber) has its own regulators with its own parameters (proportional P, integral I, derivative D), depending on their system dynamics. The control requirements during the compression and treatment bottom steps are different, leading us to design and implement 3 regulators for each compartment combination, coming to 18 different regulators.
The use of PLCs makes possible to perform different simultaneous treatments running in the different chamber compartments. For example, in case of the arrival of an emergency patient (e.g. a diving accident) during a standard treatment the ICU can be used to carry out the emergency treatment, while the standard HBO treatment can go on normally and correctly.

Some of the main automated procedures are described below. Fig.4 shows the automatized procedure implemented in order to begin a HBO treatment. First of all, the PLC checks the main elements of the installation (communications, sensors, valves, security elements, compressors pressures, oxygen circuit pressure, etc). If any anomaly is detected, the treatment cannot begin and the breakdown must be fixed. In case there is no breakdown or it has been fixed, a pressure profile is chosen and it is loaded to a compartment volume combination (e.g. pre-chamber + main chamber). Once the patients are ready inside the chamber and the doors are closed, the treatment starts. A supervised control is carried out, that is to say that the controller tracks the pressure profile while it is supervised by technical and medical staff, which can decide whether it is necessary to perform one of the described procedures and protocols.

Figure 5 describes the alleviation procedure. When the alleviation procedure is pressed, a decompression profile is loaded to the decompression regulator which decreases the pressure a determined value following a determined decompression ratio. For example, if pressure is 1.45 bar at the moment of pressing the alleviation button, the alleviation value is 0.05 bar, and the decompression ratio is 0.1 bar/minute, the regulator will decrease the chamber until 1.40 bar in 30 seconds. When the alleviation is finished, it is possible to carry out another alleviation or to resume the treatment.

Figure 6 describes the automated pre-chamber procedure, which is used to take out a patient or to enter medical staff during a HBO treatment. The proceeding to take out a patient is described. A decompression profile is chosen depending on the urgency, the patient is placed inside the pre-chamber, and the pre-chamber doors are closed. Just in the moment when the pre-chamber pressure is less than the pressure in the other compartments, the profile is loaded to the ICU regulator and to the main chamber regulator. Thus, the ICU and main chamber continue normally the treatment, but each one with a different regulator as simultaneous treatments. When the pre-chamber reaches atmospheric pressure, its door opens and the patient can leave the chamber. Afterwards, the pre-chamber is pressurized following a selected profile until it reaches the ICU and main chamber pressures and in that moment the pre-chambers doors are opened and the profile is loaded again to the original controller (ICU + pre-chamber + main chamber).

It is worth pointing out that the procedures mentioned before can be carried out in any compartment without affecting other simultaneous treatment performed in other compartment.

2) Automation and Control Program: The programmable logic controller chosen to automatize and to control the hyperbaric chamber is a Siemens IM 151-8 PN/DP CPU interface module. The control program has been developed using Siemens STEP7 and the language used is AWL (list of instructions language). The Standard PID Control library [8] consist of two FBs (Function Blocks) which contain the algorithms for generating control and signal-processing functions for continuous or step controllers.
In this case the continuous control FB41 (CONT-C) block is used. This block [8] must be used to control processes with continuous input and output variables. The proportional, integral (INT), and derivative (DIF) actions are connected in parallel and can be activated or deactivated individually. This allows P, PI, PD, pure I, pure D, and PID controllers to be configured.

In order to load the reference (or setpoint) pressure profile to the PID, the Ramp Soak (RMP-SOAK, FB21) function has been used. This block is used to have the setpoint changed automatically over a period of time. The ramp soak RMP-SOAK supplies the output variable OUTV (Fig.7) according to a defined schedule. This function is started by setting the input bit RMP-SK-ON. If the bit for cyclic repetition CYC-ON is set, the function is started again at the first time slice outv[1] after the last time slice outv[NPR-PTS] has been output [8].

The sequence of the ramp soak is defined by specifying time slices in a shared data block with the time values PI[i].TMV and the corresponding output values PI[i].OUTV. (Fig.7).

The time slice parameters NPR-PTS, PI[i].TMV and PI[i].OUTV are located in a shared data block [8]. In the STEP7 project it is only necessary to have the FB21 RMP-SOAK block and a DB block associated to FB21 for each compartment combination.

Once it is calculated by the corresponding function block, the pressure profile is loaded as a two-dimensions matrix (time, pressure) to the RMP-SOAK blocks. The pressure profile points are calculated each 0.02 seconds of treatment.

With RMP-HOLD=TRUE it is possible to freeze the value of the output variable, including the time processing. When this is reset (RMP-HD=FALSE), the ramp soak continues at the point of interruption. This functionality is used to carry out the pause procedures.

It is possible to select the time slice and time to continue when pause is done. If the control input CONT-ON is set to TRUE, the signal continues at the time TM-CONT with the time slice TM-SNBR. The time parameter TM-CONT determines the time remaining that the ramp soak requires until it reaches the destination time slice TM-SNBR [8].

The CONT-ON functionality has been used to implement the alleviation procedures. During alleviation procedures the setpoint ramp soak is paused, and a new short ramp soak is loaded to the regulator in order to decompress the chamber. When the alleviation is finished, the treatment profile ramp soak continues from the closest point to the actual pressure after the alleviation.

A. Cross-Platform Open Source SCADA

The aim of the SCADA (Supervisory Control and Data Acquisition) is to supervise and control the automated HBO treatments. The Siemens IM151-8 CPU communicates with a multi-platform OPC UA [2] via TCP/IP using the open source Libnodave library. This OPC UA, which is developed using the PyOPC library [4][5], is used to communicate the PLC with the SCADA application and it is also prepared to communicate with other computers, OPC servers, PLCs, and mobile devices (smart-phones and tablets). The SCADA graphical interface is developed using the Qt Designer tool, the PyQt libraries and the Python programming language.

1) Siemens Simatic S7 TCP/IP Communication: Libnodave Library: Libnodave [6] is a library that provides the necessary functions to connect to and exchange data with Siemens S7 300/400 PLCs. Data exchange comprises all memory areas and variables in the PLC programs, e.g. flags, data blocks, input and output image memory, timers and counters. Libnodave is free software under GPL and LGPL. It is currently available for UNIX and Win32.

2) SCADA Interface Development: The SCADA graphical interface is developed using the Qt Designer Tool (interface graphical design), the PyQt libraries (bindings for Qt application framework) and the Python programming language.

Python is a programming language that lets working more quickly and integrating the systems more effectively. Then main advantages of using Python are immediate gains in productivity and lower maintenance costs. Python runs on Windows, Linux/Unix, Mac OS X, and has been ported to the Java and .NET virtual machines. Python is free to use, even for commercial products, because of its OSI-approved open source license.
Qt [1] is a set of C++ libraries and development tools that includes platform independent abstractions for graphical user interfaces, networking, threads, Unicode, regular expressions, SQL databases, SVG, OpenGL, XML, and user and application settings. PyQt implements 440 of these classes as a set of Python modules. PyQt [3] is a set of Python bindings for Nokia’s Qt application framework and runs on all platforms supported by Qt including Windows, MacOS/X and Linux. Qt also includes Qt Designer, a graphical user interface designer. PyQt is able to generate Python code from Qt Designer. It is also possible to add new GUI controls written in Python to Qt Designer.

Using the previously described tools and communicating with the IM151-8 CPU, a SCADA system (see Figure 8) has been developed in order to control and to supervise the hyperbaric oxygen therapy performed in a multiplace and multicompartiment hyperbaric chamber. The HBO SCADA lets the technical and medical specialized staff of the HBO Center (in this case Medibarox HBO Center) to carry out the automatized treatments while monitoring the process variables and interfacing with the system when the treatment requires. With the SCADA it is possible to configure the treatment profile and to run it smoothly in a very easy and intuitive way, while it shows all the information to describe accurately the state of the treatment.

III. RESULTS AND DISCUSSION

A robust an stable automated system has been developed. It is able to track accurately pressure profile even the most complex profiles, which can also be carry out simultaneously (different treatments running in the different chamber compartments at the same time) without compromising its correct operation. Figure 9 shows a real hyperbaric therapy carried out with 25 patients. As can be seen, the pressure inside the chamber follows the profile accurately. The RMS control error of treatment in Fig.9 is 0.012%. The smoothness of the control signal is also an important factor, because the noise and air flows inside the chamber are minimized. The repeatability of treatments and experiments are now possible, which makes it possible for doctors to design new treatments for different diseases and obtain conclusions by applying these treatments to other patients.

The HBO procedures described in section II-1 have been implemented in AWL language, making possible to carry out more safely and accurately all these multiplace and multicompartiment important protocols, which before this work were very difficult to do. Figure 10 shows the pressures of a Medibarox Hyperbaric Center’s treatment where different automated procedures were required due to some problems with a patient who had difficulties compensating pressure changes because of eustachian tube obstructions produced by mucosity. Firstly, a pause was done in order to decide whether the patient could continue his treatment, because he was having some earache. The patient was supposed to be OK, thus the pressure profile kept on pressurizing until the patient required two alleviations, so he could compensate the ear volume change. After this two alleviations the treatment continued, but the patient could not put up with the pain so the clinical staff decided to take him out. In that moment, a pre-chamber procedure was carried out. The patient was placed inside the pre-chamber and its doors closed. When the control program detected the doors closing, a depressurization profile was loaded to the pre-chamber’s regulator and, as it can be seen in Fig. 10 (orange line), the pre-chamber was reduced to ambient pressure. While the pre-chamber procedure, the ICU and main chamber were separated and each regulator tracked the same pressure profile. The patient was evacuated and a new pressurization profile loaded to take the pre-chamber to the ICU and main chamber pressure. When the pre-chamber reached the 2 ATA pressure,
its doors were opened and the whole chamber regulator could continue with the profile. When the treatment was finished, the depressurization step took the pressure to the atmospheric pressure. The most important result, which is a very important advantage respect to the traditional multiplace and multicompartiment chambers, is the possibility to carry out automated complex procedures without compromising the robustness and smoothness of the control, and therefore the safety and well-being of the patients.

![HBO treatment with alleviations and pre-chamber procedure](image)

Fig. 10. Medibarox Hyperbaric Center’s chamber alleviations and real pre-chamber procedure.

IV. CONCLUSIONS

Hyperbaric oxygen therapy is a field of medicine with a future. Oxygen is the element that keeps people alive, and when used as medicine under hyperbaric pressures it can cure a wide variety of diseases. Hyperbaric medicine is the starting point, and with the help of technology and scientific research it will become more popular with both doctors and patients. It is, therefore, an incipient therapy that requires resources for its research.

The Medibarox Hyperbaric Center’s chamber is currently working automatically with the described control architecture, where two redundant PLCs run the control program, and the medical and technical Medibarox’s staff supervise the treatments with the designed SCADA and touch HMI. Treatments are currently carried out automatically and safely, and profiles are followed in a much smoother manner than before.

Automatic pressure control permits doctors and researchers to design complex treatments, thus ensuring that the profiles are successfully followed, and making repeatability possible. This opens up large research possibilities and the consequent realization of new therapy treatments and personalized profiles for people with special conditions and a wide variety of diseases. As a result of the automation and pressure control of the chamber, new complex curve profiles designed for neurological diseases are being arranged and pediatric patients can be treated successfully. Moreover, established standard treatments are carried out with less problems, with more thermal comfort, less noise, more accuracy and more safely. The number of barotraumas and patients that required to abort their treatments has also been reduced drastically.

The system has been tested and it is successfully working in Medibarox since May 2011 carrying out four treatments a day, 540 standard HBO sessions with a mean of 25 people each one, and 180 special treatments with patients with neurological diseases. During this period of time special patients have been treated (pediatrics, neurological diseases, and patients with tracheostomies).

In conclusion, the results presented in this paper are an important step and a significant improvement. The disadvantages of hyperbaric oxygen therapy have been overcome, making possible to treat patients that before were unthinkable to treat, or allowing repeatability and in the near future they will make new research works possible in fields such as oncologic-HBO combined treatment.

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